# High Accuracy CMM Measurements of Large Silicon Spheres

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## Abstract.

The NIST M48 coordinate measuring machine (CMM) was used to measure the average diameter of two precision, silicon spheres of nominal diameter near 93.6mm. A measurement technique was devised that took advantage of the specific strengths of the machine and the artifacts while restricting the influences derived from the machine's few weaknesses. This effort resulted in measurements with unprecedented accuracy and uncertainty levels for CMM style instruments. The results were confirmed through a blind comparison with another national measurement institute (NMI) that used special apparatus specifically designed for the measurement of these silicon spheres and employed very different measurement techniques. The standard uncertainty of the average diameter measurements was less than 20 nanometers. This paper will describe the measurement techniques along with the decision-making processes used to develop these specific methods. The measurement uncertainty of the measurements will also be rigorously examined.

## 1.0 Introduction.

The kilogram is the only remaining fundamental unit within the International System of Units which is defined in terms of a physical artifact, a Pt-Ir cylinder kept in the International Bureau of Weights and Measures (or BIPM) in Paris. There are several ongoing attempts to redefine the kilogram independent of the artifact along with other exploratory projects in the density field that are very closely related to the kilogram efforts. The preferred objects used for this work are finely polished single crystal silicon spheres with a mass of very near one kilogram. This results in a spherical diameter of about 93.6mm. The spheres are manufactured at the Australian Center for Precision Optics (APCO), a facility located within the Commonwealth Scientific and Industrial Research Organization (CSIRO); the national measurement institute of Australia. A typical APCO silicon sphere has roughness characteristics of 0.2 RMS and a sphericity of less than 50nm RMS. Measurements were recently performed at NIST on two APCO silicon spheres. The NIST measurement process was dramatically different in that it used commercially available measuring equipment and measurement methods. The NIST measurements were performed using the flexible, stylus-based Moore M48 coordinate measuring machine [1].

The machine is housed inside a specially built thermally controlled room. This room maintains a constant 40 % (± 2 %) and a constant 20.00 degree Celsius temperature (± 0.02 ºC) within the volume of the room over a 24 hour timespan. The room has a quick air exchange rate and maintains a constant laminar flow from ceiling to floor. The indirect lighting fixtures are sealed and are kept at low light levels while air is moved through the fixtures and removed from the room to minimize any convection and radiant heating from the lights. Additional fans are used to reduce thermal gradients around the M48 table surface and under the cross bridge. These techniques result in thermal gradients of less than 10 millidegrees within the full 1000mm x 600mm x 300mm measurement volume of the machine. Constant temperature air is also pulled through the machine through several ducts to maintain constant temperature on the inside surfaces as well as the outside surfaces. The machine temperature environment is monitored through a series of 14 sensors placed in and around the machine. Index of refraction corrections are made to the laser outputs using state of the art pressure and temperature monitoring equipment.

Key to the exceptional performance of the M48 is the reproducibility of the error map. The map currently holds terms for the scale, pitch, yaw, and roll errors of each machine axis as well as the measured squareness and straightness motion errors of the axes. Mapping a machine like the M48 presents some unique problems. The exceptional raw motion accuracy of the M48 requires that the mapping exercise be performed independent of the machine controller supplied mapping options to increase the sensitivity of the corrections. The stability of the machine error map is quite good. Because the machine has not moved from its floor position for over 14 years, the advantages gained by the M48 physical design, room control, and footprint stability allow the map to remain stable for long periods of time.

## 2.0 The Measurement Method.

The development of the CMM measurement method for the silicon spheres was complex. The inherent flexibility built into a CMM becomes a distinct disadvantage when trying to achieve accuracy at a level of several nanometers. It was evident that to achieve the accuracy requirements of the spheres it would require a very unique approach with some novel measurement techniques. The final measurement plan naturally separated into two distinct paths of focus. First, the strengths of the machine, such as the smooth mechanical motions, the room environment, and the repeatability characteristics, were exploited as much as possible. Historical measurement data has proven that the M48 performs very consistently and is very repeatable over long periods of time. The machine also behaves very predictably as a result of internal heating effects during these long measurement runs. Second, any unaddressed and multi-axial errors should have their influences on the measurement results minimized as much as possible. Historically, the M48 has excelled during 1D comparison-style operations where the flexibility of the machine is severely restricted. The challenge for the sphere measurement method was to approach this ideal as closely as possible.

Three stainless steel spheres were selected as master artifacts and calibrated along a specific two-point diameter using the NIST Strang Interferometer [2]. The nominal sizes of the stainless steel master spheres, 25.4mm, 19.05mm, and 12.7mm, were selected for several reasons. The spheres needed to be large enough so that they could be rigidly mounted on the CMM work-surface using existing mounting fixtures. These fixtures hold the spheres in a kinematic, 3-ball magnetic mount that allows unobstructed access to the equator of the spheres. This configuration was optimized for using 25mm diameter spheres and was modified to accept smaller spheres while maintaining a rigid stability during touch probe measurements. Using multiple mastering artifacts also facilitates the sampling of the unmapped CMM positioning errors during the silicon sphere comparison process.

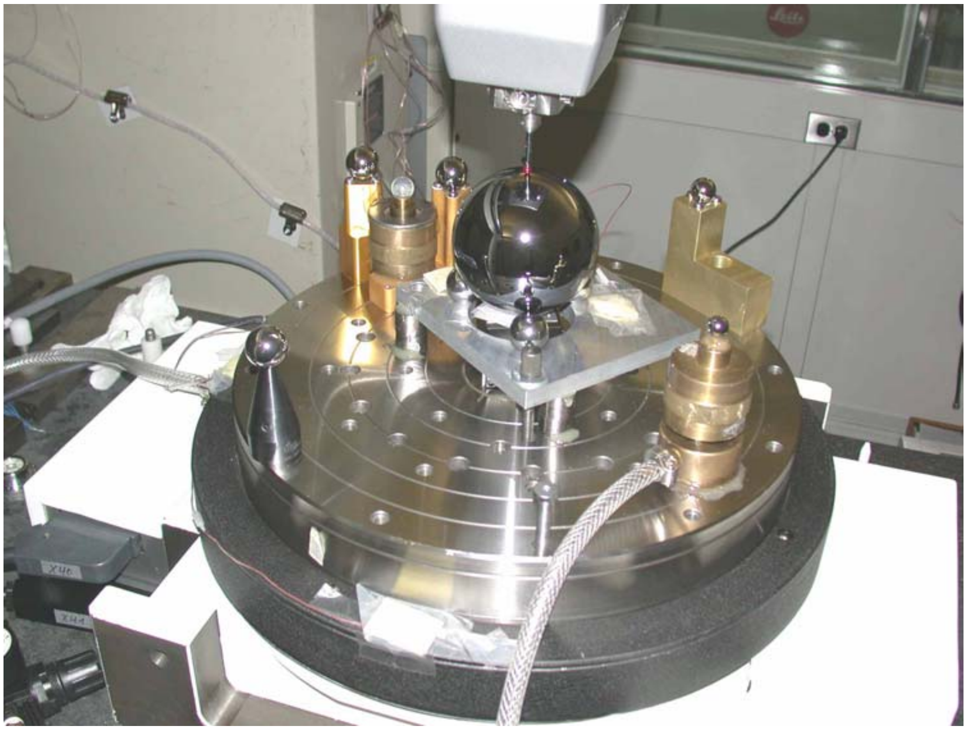

Figure 1. The artifact measurement setup on the rotary table.

A novel technique was devised to facilitate the requirement of 1-D data collection and is shown in Figure 1. The probe deflection sphere, the three stainless steel master spheres, and the silicon sphere were mounted on a precision rotary table interfaced to the CMM machine controller which allowed for the rotary table to be positioned and controlled automatically during the data collection. The silicon sphere was specifically mounted directly central to the rotation axis of the table. This assured that when the table was rotated to predetermined angular positions, the two-point diameter measurements of the silicon sphere were still performed directly along the proper central axis of the sphere without having to redefine the sphere's central location. The mounting technique was designed so the sphere could be removed and replaced without damage to the delicate surface. The sphere was set on a cork pad on the top of a precision jack that could be slowly lowered and centered so the silicon sphere could be directed to make contact with the three kinematic mounting points at the same time. This minimized the impact to the sphere and the possibility of damage to the surface. The three master spheres were positioned in different locations around the rotary table such that the calibrated diameters were located parallel to the machine X-axis. This setup allowed for these initial master sphere locations to be relocated easily if the rotary table moved to other angular positions and could be redundantly re-measured at the exact location identified in the initial interferometric measurements on the Strang monochromatic viewer.

The unique measurement procedure combined redundancy and repeatability into a thermal drift eliminating data collection design. Following the initialization of the probe bending and deflection variables, the three stainless steel master sphere locations were determined and two-point diameter measurements was repeatedly collected for each along the machine X-axis. The silicon sphere location was then determined and a two-point diameter was also repeatedly measured along the machine X-axis. The silicon sphere was then rotated at 15-degree intervals and subsequent two-point diameter measurements were repeatedly collected along the same probe and machine X-axis at these new radial positions. Following each 15-degree interval, silicon sphere diameter measurement, the rotary table was moved to the original position and the three master sphere two-point diameters were again re-measured. This process was run through a 180-degree rotation of the silicon sphere then run in the reverse direction to provide a thermal drift elimination technique to the data set. The silicon sphere data collected during any single measurement sequence resulted in basically a 13-point average diameter around a single cross-sectional plane of the sphere. The repetitive measurements of the master spheres provided a good averaging of the master sphere values and brought any probe repeatability and drift concerns along with any machine repositioning inaccuracy into the random fluctuations of the data set.

The final very important advantage to the rotary table setup was for sampling any uncorrected CMM positioning errors and silicon sphere roundness errors. Concentrating all measurement artifacts onto the rotary table surface allowed for the easy repositioning of the whole rotary table assembly on the CMM table. The rotary table was moved to nine locations around the CMM work surface thereby sampling any positional dependent systematic errors into the random fluctuations of the data set. The control program only required the new locations of the spheres within the work volume to be redefined to the CMM controller resulting in a very efficient process. The silicon sphere was also rotated in the mount through the three orthogonal axes in addition to other random positions and measured with the rotary table at a fixed position. These tests result in constant machine error behavior and the effects of sphere geometry were independently derived.

## 3.0 The Measurement Data.

The data analysis for the first silicon sphere indicated an average diameter of 93.611471 mm. The result from the independent measurements performed at CSIRO in Australia was 93.611461 mm. The NIST measurements were 10 nm larger.

The data analysis for the second silicon sphere indicated an average diameter of 93.610218 mm. The result from the independent measurements performed at CSIRO in Australia was 93.610215 mm. The NIST measurements were 3 nm larger.

The agreement between the NIST and CSIRO measurements was excellent.

## 4.0 Measurement Uncertainty Calculations.

The difficult task of calculating the uncertainty for a coordinate measuring machine measurement can be streamlined for 1-D measurements performed along a single axis of the instrument. Most of the complicated three-dimensional errors relating to instrument positioning, datum generation, and probe-based coordinate errors are reduced to only single axis effects that can be much easily measured. In addition, by using the CMM as a comparator rather than an absolute measuring instrument, the error budget can be reduced to a managable collection of error sources.

The uncertainty components are compiled in the Uncertainty Budget Table 1.

| Error Component | Standard Uncertainty (k=1) in Nanometers | Brief Description |
|---|---|---|
| Master Artifacts | 9.7 | Uncertainty for single-point diameter measurements on the Strang Interferometer. |
| CMM Laser Scale Index of Refraction Error | 0.06 L | Uncertainty in the Edlen Equation, laser wavelength, beampath temp., pressure, and humidity for index of refraction calculations. |
| CMM Scale Mastering Error | 0.100 L | Limitation by the combination of historical performance verification and long end standard artifact uncertainty. |
| Elastic Deformation Predictions | 5.8 | Rectangular distribution of a ± 10 nm experimentally determined performance vs. predicted elastic behavior. |
| CMM Uncorrected Positional Errors | 8.3 | Multiple technique, experimentally determined performance of 25 nm reduced by √9 where 9 is the number of independent machine positions sampled in the average calculations. |
| Silicon Sphere Form Errors | 5.1 | Diameter measurements at six random planar positions. The 25 nm range was reduced by √6 term for the average calculations. |
| CMM Positioning and Probe Repeatability | Neg. | Error source adequately sampled in CMM positional error term. |
| Probe Mastering Error | Neg. | Either negligible for 1-D measurements or previously sampled. |
| Silicon Sphere Centering Error | Neg. | Total run-out contained to less than 3 µm results in negligible effect. |
| Surface Finish Effects | Neg. | Si sphere Ra = 0.2 nm, master spheres Ra = 25 nm. Triggering force results in predictable bulk material elastic behavior range. |
| Silicon Sphere CTE Uncertainty | 0.5 | 10% unc. in bulk material property, meas. temp. of 20.02°C.<br>u(F) = (0.1)(2.6 ppm/°C)(93.5mm)(20.00°C - 20.02°C) |
| Master Spheres CTE Uncertainty | 0.4 | 10% unc. in bulk material property, meas. temp. of 20.02°C.<br>u(G) = (0.1)(10.5 ppm/°C)(19.05mm)(20.00°C - 20.02°C) |
| Thermal Gradients | 1.2 | 5 millidegree gradients measured in setup area.<br>U(H) = (.005°C)(2.6 ppm/°C)(93.5mm) |

Table 1. Silicon sphere measurement uncertainty budget.

Combining these terms gives a combined standard uncertainty of ± 18.0 nm.

This results in an expanded uncertainty using a coverage factor of k=2 for the average diameter measurement of the silicon sphere of ± 36 nm. This is an outstanding result for a CMM style measurement.

## 5.0 Conclusions

The performance of the NIST M48 Coordinate Measuring Machine in the average diameter measurements of two exceptionally fine 93.6mm silicon spheres was outstanding. The M48 measurements agreed very well with independent measurements using very specialized equipment and very different techniques. The unprecedented quality of the artifact's geometry and surface finish allowed for a rigorous analysis of some very small and difficult to isolate measurement uncertainty sources in the operation of the M48 CMM. This analysis combined with the restricted design of the measurement methods and the inherent accuracy of the M48 resulted in measurements with a very low measurement uncertainty. It is expected that other current measurement requirements using the M48 CMM, such as large 2D gridplates and pressure piston and cylinder combinations will immediately benefit from this work. Measurement uncertainties for these and other measurements using the M48 CMM will be reduced based on that information learned about the very fine positional and reproducible motion accuracies of the machine.

## 6.0 References

1. Trade names and company products are mentioned in the text to specify adequately the equipment and procedures used. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the products are necessarily the best available for the purpose.

2. Stoup, J.R., Faust, B., Doiron, T.: Minimizing Errors in Phase Change Correction Measurements for Gage Blocks using a Spherical Contact Technique. SPIE Proceedings - Recent Developments in Optical Gauge Block Metrology, San Diego, pages 162-163, 1998.